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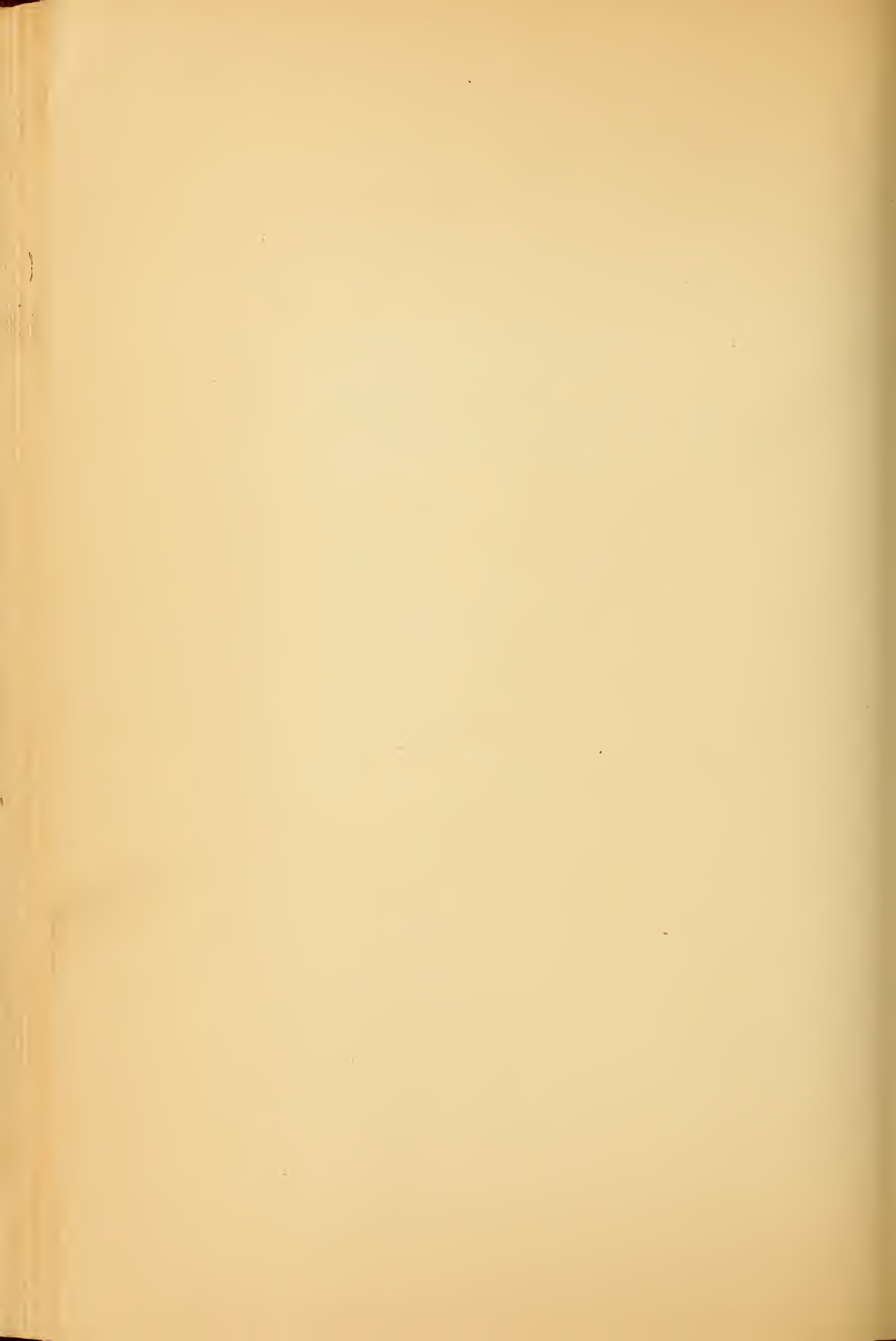


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/Bulletin of the Bureau of Standards
QC1 .U5 V2:1906 C.2 NBS-PUB-C 1905







A NEW POTENTIOMETER FOR THE MEASUREMENT OF ELECTROMOTIVE FORCE AND CURRENT.

By H. B. Brooks.

1. INTRODUCTION.

Instruments for the measurement of electromotive force and current may be divided into two main classes. In those of the first class, which may be called deflection instruments, a movement of one element of the instrument is produced against an opposing force, an indication of the quantity to be measured being given by the extent of the motion, as shown by an index moving over a graduated scale. To this class belong many types of ammeters and voltmeters, such as the moving coil, the magnetic vane, electro-dynamometer, hot wire, and electrostatic instruments. Those of the second class may be called balance instruments. In these the electric quantity to be measured exerts a force which is opposed by another force, an adjustment of the instrument being made until no motion results, when the quantity to be measured is determined by the extent of the necessary adjustment. To this class belong Wheatstone bridges, potentiometers, and Kelvin balances.

Each of these two classes of measuring instruments has its advantages and disadvantages. The deflection instrument can not be read, as a rule, with an accuracy greater than one part in a thousand; while on account of zero errors, inaccuracy of the scale, heating due to the current, changes of external temperature, stray magnetic fields, and other disturbing influences, the accuracy really obtained in the result is much lower than this. It is possible, of course, to determine and allow for some of these errors, but others, such as those due to stray field, are not easily allowed for. The balance instrument can usually be read with greater accuracy, and in the

case of the potentiometer the accuracy of reading may be carried to almost any desired extent by using a sufficiently sensitive galvanometer.

Instruments of the deflection type are, as a rule, more liable to change their constants with time than those of the balance type. This is especially true of the moving coil instrument, where magnet and spring are subject to changes which affect the readings. Besides a gradual change in the strength of the magnet as time goes on, and sudden changes due to blows, a temporary change in the strength of the magnetic field in which the coil moves may be produced by heavy currents in conductors near which the instrument may be used or by the stray field from other instruments. Balance instruments, on the other hand, usually retain their calibration very well, and are not affected, either temporarily or permanently, by disturbing influences which seriously affect the other class.

Deflection instruments are especially useful in commercial work where great accuracy is not required. They have the advantages of requiring no special setting up, of being quickly read, and of always indicating, approximately at least, the value of the quantity to be measured. Balance instruments are particularly useful in laboratory work where accuracy is essential, and where steady electrical conditions can be maintained. Their use requires much time, as every change in the quantity under measurement requires an adjustment to be made for the condition of no deflection. In the determination of unknown masses, first by a spring balance and second by the equal arm balance, using standard masses, we have conditions similar to those attending the use of the two classes of electrical measuring instruments.

2. THE POTENTIOMETER METHOD.

For precision measurements of direct current and electromotive force, in terms of standards of electromotive force and of resistance, the potentiometer method excels in accuracy, flexibility, and range of application, and it is to-day the standard method for such measurements. The potentiometer is unaffected by external disturbances, if we except the effect of leakage currents, which should be guarded against. Its accuracy is dependent upon the accuracy of adjustment of resistance coils, and its permanency of calibration depends upon the

constancy of the relative values of these coils, and the constancy of the standard cell used. Resistances may be adjusted and compared with an accuracy much greater than that obtained in other electrical measurements, and the errors in the coils may be determined and allowed for at any time in accurate work. Standard cells, while not in a perfectly satisfactory condition at present, are readily compared with each other with great accuracy, and when properly made are very reliable.

On the other hand, the disadvantages of the potentiometer method are the time required to make the measurements, the bulk and cost of the apparatus, and the fact that the current or voltage must be kept steady while being measured, it being practically impossible to use a potentiometer on a circuit where the current or voltage is subject to fluctuations of any magnitude. Attempts have been made from time to time to introduce potentiometers for use as standard instruments in central station and similar work. An interesting example is the Howell voltmeter, used in early Edison stations. This was a portable potentiometer in compact form, comprising galvanometer, standard cell and resistance coils, one of these coils having a sliding contact, the position of which, when the galvanometer showed no deflection, was an indication of the pressure at the instrument terminals. One form of this instrument was small enough to be carried in a coat pocket. Special Daniell cells were used at first, and later a form of Clark cell, a thermometer being necessary with the latter.

Attempts have been made from time to time to introduce in practice more elaborate forms of portable potentiometer as standard instruments for use in checking deflection instruments; but these attempts have not met with entire success. The need unquestionably exists for a type of instrument for current and voltage measurements which will have properties intermediate between those of the ordinary deflection instrument and the elaborate potentiometer. For example, in reading ordinary portable ammeters and voltmeters the limit of accuracy of reading, for, say, two-thirds of full scale deflection, is about one part in a thousand. For checking these a standard instrument which can be easily read to this degree of accuracy and estimated five times further is amply sensitive. To meet this need there has been offered a larger form of deflec-

tion instrument for current and voltage measurements, to which the name "laboratory standard" has been applied. While the larger dimensions allow the heat generated to be thrown off with a smaller rise of temperature, and the longer pointer allows a somewhat more accurate reading of the deflection to be made, these instruments are not entirely satisfactory for the purpose for which they were produced, and for careful work need to be checked by a potentiometer at rather frequent intervals, under the conditions of use. These instruments are affected by stray field and other disturbing influences in the same way as the smaller instruments, though not to as great an extent.

The standard instrument should however be practically free from the sources of error which affect the deflection instrument, and should be so constructed that its constants will not be liable to alter with time. It should be possible to use it even on circuits that are not steady, and it should require as little manipulation as possible. It should be compact, simple, and not too expensive, and it should be made so as to be readily checked. In other words, it should combine as much as possible of the convenience of the deflection instrument and the accuracy and constancy of the potentiometer. Such an instrument would be useful in the central station, for the checking of portable and of switchboard instruments, some forms of which latter should be tested in position under the conditions of use. It would be of service in the instrument factory, where a large number of instruments must be tested, and in the laboratory, for measurements in which a greater degree of accuracy is required than can be had using deflection instruments. It would be of service in photometry, where a degree of accuracy in voltage measurements is needed which is obtained with deflection instruments only by great care in reading and by constantly falling back upon the potentiometer as a check on the relatively large changes, due to heating and other causes, which occur in the best deflection instruments. Other uses might be mentioned, but it is evident from the above that a field exists for an intermediate type of instrument.

3 THE DEFLECTION POTENTIOMETER.

With the above requirements in mind, it occurred to me that a satisfactory instrument for this work might be realized by using the potentiometer method to measure the bulk of the electrical

quantity, in conjunction with a suitable deflection instrument to measure the small remainder, which may be of the order of 1 per cent of the total.¹ For example, if an electromotive force is between 110 and 111 volts, the potentiometer method may be used to measure the 110, the decimal part being read by deflection. The potentiometer is essentially a null instrument, and the function of the galvanometer ordinarily is to show, by the absence of a deflection, when the unknown electromotive force is compensated by the known. In some cases, however, as in measuring low electromotive forces, we desire to read one more figure in addition to that given by the lowest dial; and in such a case, with some forms of potentiometer, we may interpolate between adjacent settings on this dial, just as we interpolate in Wheatstone bridge and other resistance work. In doing this we assume that within this narrow range the deflection is proportional simply to the unbalanced portion of the electromotive force. In the present case the problem is to determine the conditions to be met, first, in order that the deflection corresponding to a given unbalanced electromotive force may always be the same, regardless of the setting of the potentiometer dials; and, secondly, in order that the deflection should be strictly proportional to the unbalanced electromotive force for a relatively large unbalancing, as it is ordinarily assumed to be for a small unbalancing.

To reduce the necessary manipulation to a minimum, there should be but one dial to be set, one step of which covers from 1 to perhaps 5 per cent of the total range. In the latter case, to secure an accuracy of one-twentieth of 1 per cent, the deflection instrument must measure the unbalanced 5 per cent with an accuracy of 1 per cent. If the steps on the main dial are not so large, the accuracy required in the galvanometer is not so great.

¹The idea of balancing the larger portion of an unknown emf. by the potentiometer method, the remainder being indicated by the deflection of a galvanometer, was suggested by Stansfield and used by him in the construction of a recording pyrometer. (*Phil. Mag.* 5, 46, p. 59, 1898.) In his apparatus a Clark cell of large size was used to furnish the working current through the potentiometer wire, and it was necessary to have a second potentiometer to determine the value of this current. More recently the same idea has been used for pyrometric work by Hoffmann and Rothe. (*Zs. für Instrumentenkunde*, Sept., 1905.) In their apparatus also the indication of the galvanometer does not give at once the value of the unknown emf., auxiliary observations and calculations being required.

4. THEORY OF THE DEFLECTION POTENTIOMETER.

Assuming that the instrument is to be used for measuring electromotive forces higher than those of a single cell, a "volt-box" will be required, as shown in Fig. 1, in which E is the unknown emf. to be measured, e_1 that of the auxiliary storage cell, R the total resistance of the volt-box, the fall of potential around a fraction of this, R/p , being opposed to the fall of potential around a portion, r_1 , of the potentiometer wire AB . It was seen that to obtain the condition of constant sensibility a rheostat would be required in the galvanometer circuit, this rheostat being controlled by the motion of the main dial, represented by the slider S . For simplicity the standard cell and connections for using it to check the working current in AB are not shown, as they do not affect the problem. Assuming that the condition of balance does not exist, and denoting the currents and resistances in the various branches by $i_1, i_2, \dots, r_1, r_2, \dots$ and applying Kirchhoff's laws, we have the following equations:

$$i_1 - i_2 + i_g = 0 \quad (1)$$

$$i_4 - i_5 - i_g = 0 \quad (2)$$

$$i_1 r_1 + i_2 (r_2 + r_3) = e_1 \quad (3)$$

$$i_1 r_1 - i_g (r_4 + r_g) - i_4 \frac{R}{p} = 0 \quad (4)$$

$$i_5 R \frac{p-1}{p} + i_4 \frac{R}{p} = E. \quad (5)$$

Solving these equations, we get

$$i_g = \frac{e_1 \left(\frac{r_1}{r_1 + r_2 + r_3} \right) - \frac{E}{p}}{r_4 + r_g + \frac{r_1 (r_2 + r_3)}{r_1 + (r_2 + r_3)} + R \frac{p-1}{p^2}} \quad (6)$$

The first term in the numerator of this expression is the fall of potential in the portion r_1 of the potentiometer wire when the galvanometer circuit is open; it is therefore numerically equal to the setting of the potentiometer. The second term in the numerator is the fall of potential which would exist around the portion R/p of

the volt-box if the galvanometer circuit were open. The denominator is the total resistance in the galvanometer circuit, the third term being the resultant resistance of the portion r_1 of the potentiometer wire shunted by the remainder of the battery circuit, and the fourth term is the resistance of the portion R/p in parallel with the remainder of the volt-box, $R\frac{p-1}{p}$. Equation (6) therefore shows that the current through the galvanometer is equal to the unbalanced portion of the electromotive force divided by the total resistance of the galvanometer circuit; or

$$i_g = \frac{\Delta e}{\Sigma r} \quad (7)$$

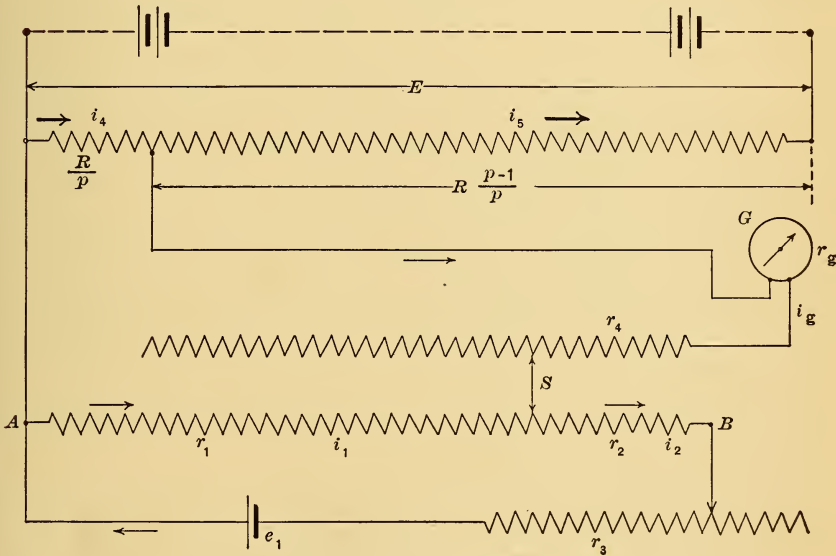


Fig. 1.—First Plan of Circuits.

Referring to equation (6), we may denote the first term in the numerator, which may be called the setting, by s . Since the volt-box has a multiplying power of p , the equation may be written in the form

$$i_g = \frac{ps - E}{p\Sigma r} \quad (8)$$

which shows that if Σr can be kept constant the galvanometer current will be directly proportional to $(ps - E)$, the difference between

the emf. corresponding to the setting and the emf. to be measured. If Σr can be kept constant for all settings, it is only necessary to calibrate the scale of the galvanometer properly to make it read directly the unbalanced part of the emf. under measurement. Referring to Fig. 1 and equation (6), it will be seen that the resistance r_4 must have such values for different positions of the slider S that the sum of r_4 and $\frac{r_1(r_2+r_3)}{r_1+(r_2+r_3)}$ will be a constant. The latter has a maximum value at some point between A and B , and minimum values at A and B ; so that r_4 must vary accordingly.

A difficulty in the way of using this particular arrangement of circuits lies in the fact that the value of e_1 depends on the condition of the storage cell, and as e_1 varies r_3 must be varied to keep the proper current through AB . This double variation of the setting and of r_3 is difficult to compensate for accurately, since for settings near A changes of r_3 make very little change in the resultant resistance, while for settings near B the changes of r_3 enter almost undiminished into the resistance of the galvanometer circuit. We may use a number of cells in place of one, giving a larger current through AB , and thus limiting the part of AB used to a relatively small portion near A . This would give a sufficiently accurate compensation for most purposes; but another arrangement of circuits may be used which does not have the objection of requiring a number of cells, one being sufficient, while the compensation for changes in the setting and in the battery rheostat may be made as perfect as desired. The plan of circuits is shown in Fig. 2.

In this arrangement the setting is made on the volt-box instead of on the potentiometer wire. The rheostat r_3 is set so as to give, by reference to a standard cell (not shown), a certain standard current through AB , and therefore a constant fall of potential around it. This fall of potential is balanced as nearly as possible by setting the slider S . The variable resistance r_4 is arranged so that r_4 plus the resultant resistance of the potentiometer circuit is a constant; r_4 thus takes care of changes in resistance required by variations in the emf. of the auxiliary cell, but is independent of the setting. The fraction $\frac{I}{P}$ being in this case a variable, the resistance in the galvanometer circuit must vary with it, as may be seen from eq. (8).

Since in this second arrangement the emf. term $e_1 \frac{r_1}{r_1 + r_3}$ is a constant, we may denote it by e . We have then

$$i_g = \frac{1}{p} \cdot \frac{pe - E}{\Sigma r} \quad (9)$$

For a difference of one volt between the setting pe and the emf. E under measurement the galvanometer is to give a deflection of m

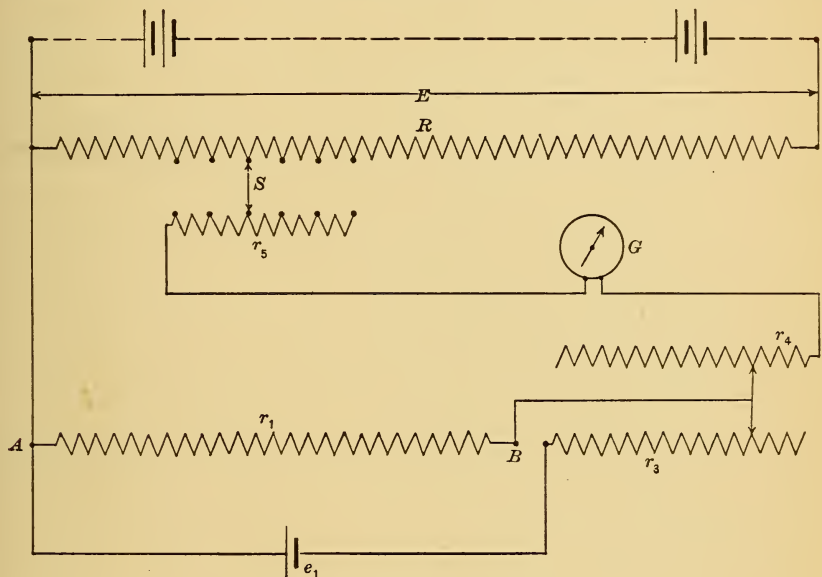


Fig. 2.—Second Plan of Circuits.

scale divisions. If I denote the current required to give a deflection of one scale division, the current mI must always flow when $pe - E = 1$. Substituting these values, we have

$$mI = \frac{1}{p} \cdot \frac{1}{\Sigma r} \quad (10)$$

$$\Sigma r = \frac{1}{pmI} \quad (11)$$

Eq. (10) shows that the compensating resistance r_5 in the galvanometer circuit, which is controlled by the movement of the slider S , must vary so as to keep the product $p \Sigma r$ a constant. Eq. (11) holds

for the first arrangement also, shown in Fig. 1; in this case, ρ being a constant, Σr must be constant and equal to $\frac{1}{\rho m I}$.

The galvanometer to be used as a part of this instrument should be of the needle type, preferably one that is pivoted and does not require an arrestment. It should have a good zero, a short period, and a calibrated scale. For laboratory use a reflecting galvanometer of short period may be used, but in many applications, as in checking switchboard instruments in position, the use of such a galvanometer would be a serious drawback, and since the high sensibility of the reflecting galvanometer is not required for the middle class of measurements for which this type of potentiometer is designed, it would seem better to use, in most cases, the more compact and easily manipulated needle instrument, which makes the apparatus portable and always ready for use. The galvanometer should have, for use in voltage measurements, a sensibility of a millimeter deflection for from two to four microamperes, unless a very high resistance is required in the volt-box circuit. The calibration of the scale should be carefully tested, as there are portable galvanometers which have fair working qualities and high average sensibility, but which have a sensibility at some parts of the scale nearly double that at others. The satisfactory working of the apparatus will depend considerably upon the working qualities of the galvanometer, and hence care should be used in selecting this instrument. A point to be considered is the value of the total resistance at which the galvanometer is aperiodic. For good results the resistance in the galvanometer circuit should be equal to or slightly greater than this resistance. In the first arrangement of circuits (Fig. 1) in which the total resistance of the galvanometer circuit is a constant, the damping may be external to any desired extent; but for the second case, with a large variation in the resistance of the galvanometer circuit, this resistance should be relatively high and the damping largely internal.

5. CONSTRUCTION OF THE INSTRUMENT.

A deflection potentiometer has recently been constructed in the instrument shop of this Bureau from my designs in accordance with the foregoing principles, and has been put into service for voltage measurements in the photometric work of the Bureau.

In this work a standard potentiometer has been used for the most accurate measurements, and it will continue to be used. The less accurate measurements had previously been made with regular portable instruments, but it was found impossible to secure the desired accuracy in this way. Portable instruments must be frequently calibrated, and must be connected to the circuit at the proper voltage for some time before use, in order to warm up and reach a steady condition. The estimation of tenths of a division requires close inspection and a relatively large amount of time, while the personal equation enters into the result. The measurement of voltage as previously carried out set a limit of accuracy to the photometric measurements somewhat lower than was desired. A potentiometer of standard form would give even greater accuracy than is required, but its use would consume too much time. The deflection potentiometer gives ample accuracy, the estimation of tenths of a division being unnecessary, and in using it for a lot of lamps of approximately equal voltage accurate readings can be taken more rapidly than with a voltmeter. If every lamp has a different voltage, the necessary adjustment of the dial would reduce the speed, but even in this case the consideration of accuracy in the work of the Bureau is given greater weight than the speed of working.

The range of this instrument is from 95 to 125 volts. Fig. 3 gives a diagrammatic plan of the circuits in the instrument. The main dial has 15 steps, each of 2 volts, the galvanometer normally covering a range of 2 volts, although it may be used over a range of 3 volts; that is, 1.5 volts on each side of the setting. To avoid errors in the photometric work the resistance R was made high, being 50,000 ohms. The resistance in the battery circuit is 2,000 ohms total when the emf. of the storage cell is 2 volts. On account of these high resistances the galvanometer sensibility required is greater than would ordinarily be necessary. The galvanometer was supplied by the Weston Electrical Instrument Company and is their regular model A, of higher sensibility than usual, giving 1 mm deflection for 1.6 microamperes. The internal resistance is 270 ohms and the period on open circuit 1.3 seconds. When in use, with its circuit closed through the potentiometer, the motion of the needle is very nearly aperiodic and readings may be quickly made.

The battery current is regulated by a rheostat of 10 steps in con-

nection with a slide rheostat for fine adjustment. The emf. of the storage cell may have any value between 1.9 and 2.1 volts. These rheostats, both dial and slide, are double, so that as resistance is added in the battery circuit it is cut out of the galvanometer circuit. A four-point switch is used to connect the galvanometer to the emf. circuit, to the standard cell through a high resistance, or to the standard cell directly. The remaining point opens the galvanometer circuit. A contact key is also provided for momentarily closing the galvanometer circuit before the balance is close enough to

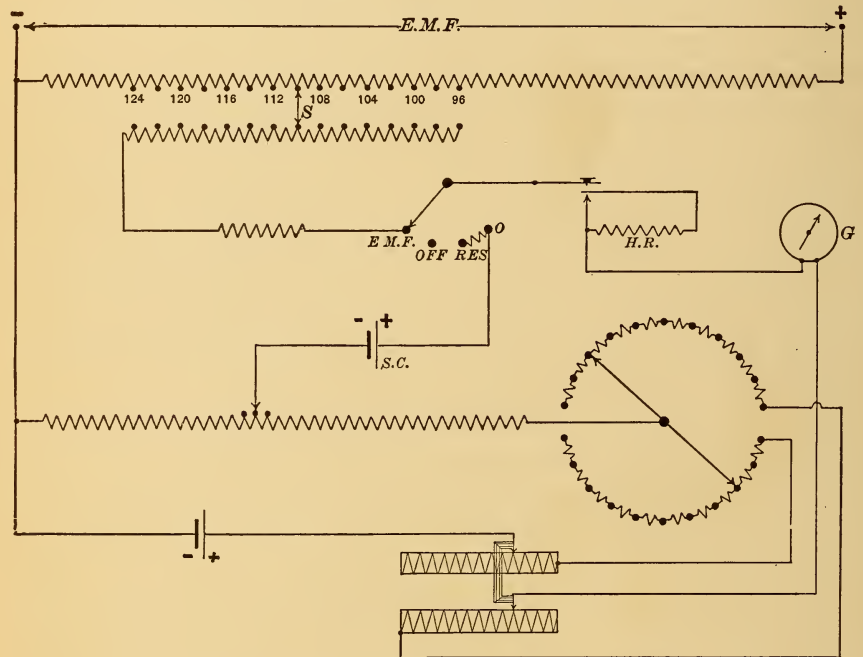


Fig. 3.—Connections of Potentiometer. (Diagrammatic.)

read the deflection. This key has an intermediate high resistance contact, as indicated in Fig. 3, and may be locked down.

A view of this deflection potentiometer is given in Fig. 4, from which it is seen that the galvanometer is built into the apparatus, so that it is self-contained, with the exception of the standard cell and storage cell. If the instrument had been intended for portable use, as in checking switchboard instruments in position, the storage cell could have been replaced by two dry cells, which with the

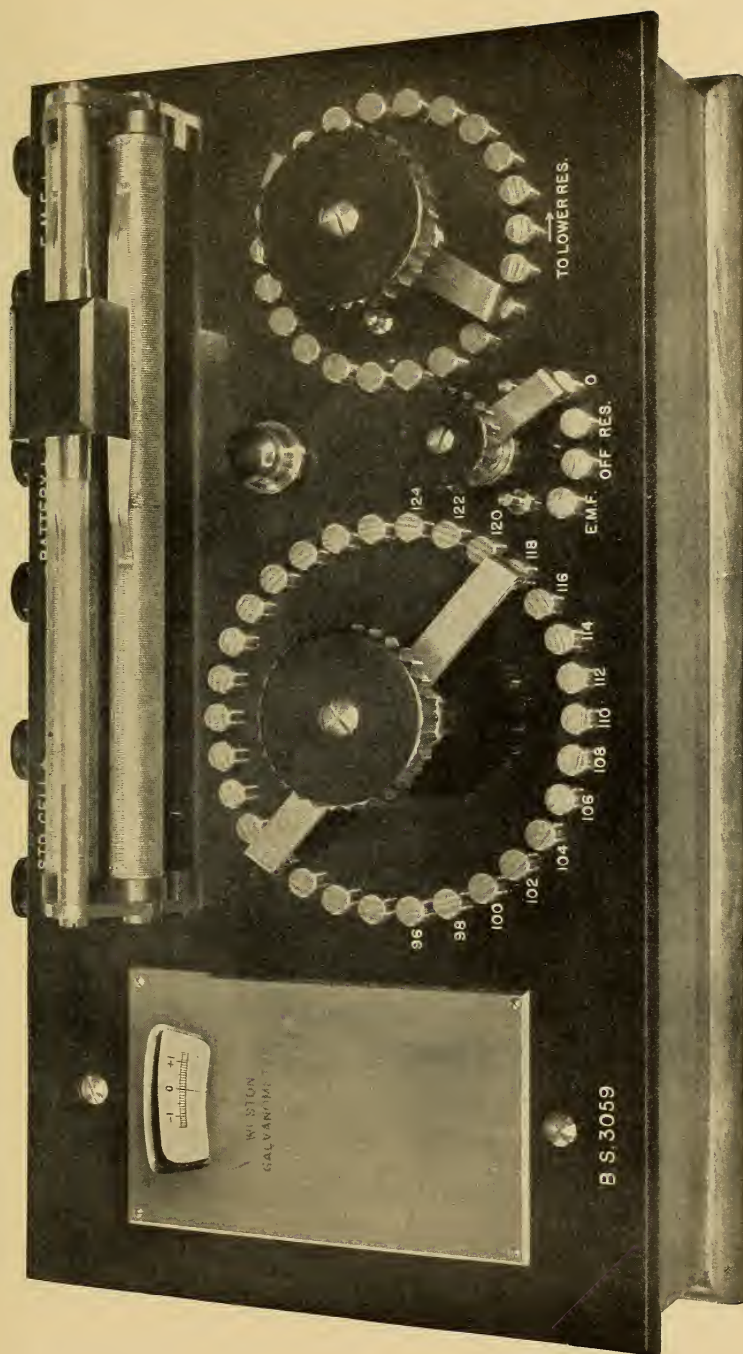


Fig. 4.—Deflection Potentiometer (Half Size).

standard cell could have been inclosed in the case, making the entire apparatus self-contained. Special precaution was taken to guard against leakage from the volt-box coils to the low-voltage circuits and the galvanometer, the guard-ring principle being used. The dimensions of the instrument are as follows: Length, 33 cm; breadth, 19 cm; height, 13.6 cm. The weight without cells is 4.75 kilograms.

A test showed that over the whole range the greatest error was 0.02 volt, the error when no deflection occurs, as at 96, 98, etc., not exceeding 0.01 volt at any point.

The design of a larger instrument of this type is under consideration. This will be used for checking voltmeters, and the dial will consequently have a greater number of points than in the instrument just described. By means of a switch the standard cell may be balanced around different portions of the potentiometer wire, giving working currents through the wire in proportion to the numbers 1, 2, 4, or whatever values may be desired. By making the volt-box so that the highest voltage to be measured will not produce undesirable heating, the same instrument may be used for various ranges, as 150, 300, and 600 volts. The details of this second instrument are not sufficiently developed at this time to give a description of it.

6. APPLICATION TO CURRENT MEASUREMENT.

It is interesting to note that while the plan of circuits shown in Fig. 1 is not convenient for use in measuring voltages higher than those of a single cell, it is the most suitable one to use in a deflection potentiometer for measuring currents. Here the fall of potential at the terminals of a current shunt is to be measured, and this fall of potential being small, it is desirable to use all of it. Further, if we were to use the plan shown in Fig. 2 for this work it would be necessary to construct a special shunt for each range, with a large number of potential points accurately located. With the plan shown in Fig. 1 any standard current shunt may be used, and it need not be an integral part of the potentiometer proper, which thus constitutes a precision millivoltmeter.

The circuits for an instrument of this kind are shown in Fig. 5. A current shunt W replaces the portion $R\rho$ of the volt-box in Fig. 1,

and only a limited portion of the potentiometer wire AB is used, corresponding to the drop in the shunt at full load, say 150 millivolts. Since only a small portion of the wire AB is used, the compensating resistance r_4 may correct for the small changes in the resultant resistance as the battery rheostat r_3 is altered, for the position of S corresponding to full load through the shunt. The compensation for smaller loads will not be theoretically exact, but the error may be made negligibly small. In an instrument for this purpose it is an advantage to use a smaller resistance in AB , in order to reduce the necessary sensibility of the galvanometer and to keep within limits the source of error just referred to. By proper design a high

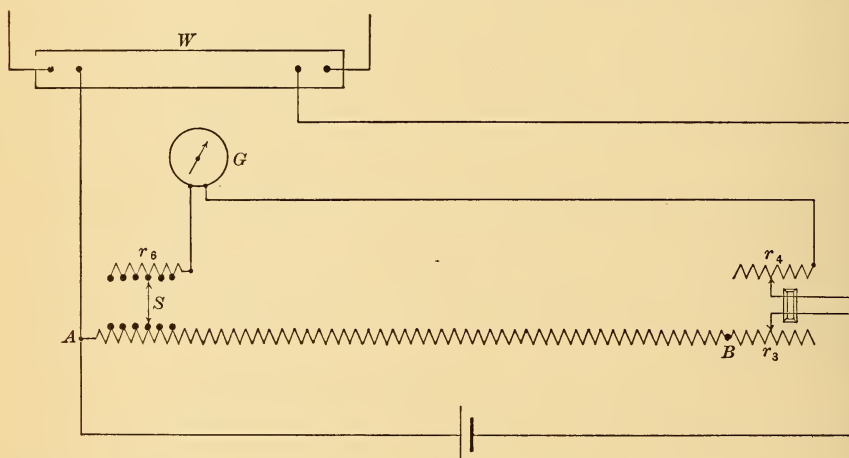


Fig. 5 —Plan of Circuits for Current Measurement.

grade of portable galvanometer like the one before mentioned, if suitably wound, will be sensitive enough, and will be of advantage when the instrument is to be used, say, for checking ammeters in position on switchboards and for use in laboratories when it is desired to have a portable precision ammeter which is independent of external disturbing forces. In heavy current tests it is usually difficult to maintain the current steady, and for such work a deflection potentiometer would be very useful, as the value of the current may be read at any moment on the standard instrument and the one under test.



